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WRI CCS Guidelines and Emerging Geologic Sequestration Regulations: A Comparative Assessment

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Abstract

Carbon capture and storage will likely be a crucial bridging technology as we move to a low-carbon global economy. The WRI CCS project was initiated to develop stakeholder consensus on policies and procedures for safe and effective demonstration and deployment of technology. This effort is taking place in the context of rapidly changing policy arena. The U.S. EPA initiated a process to develop geologic sequestration regulations and several efforts are being undertaken globally. This paper presents a review of WRI guidelines in the context of the U.S. EPA Draft Geologic Sequestration Rule and the Draft European Union Geologic Sequestration Directive.

Keywords: carbon dioxide capture and storage, geologic sequestration, risk management, guidelines

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1. Introduction

The World Resources Institute (WRI) Carbon Capture and Storage (CCS) Guidelines were developed over two years, and reflect extensive input by hundreds of stakeholders representing a variety of interests including industry, business, academia, governments and environmental groups. During the development of the WRI CCS Guidelines, global interest in CCS technology and recognition of the potential role for CCS in reducing emissions grew dramatically. The WRI CCS Guidelines are a first-of-a-kind effort to develop best practice recommendations for carbon capture, transport, and storage with significant technical detail. They were released in October 2008 in the context of emerging state and federal regulatory frameworks for geologic sequestration.

The Guidelines represent current expert understanding of how to implement CCS technologies. Importantly, the stakeholder discussions that shaped the drafting of the Guidelines were predicated on five principles:

1. Protect human health and safety,
2. Protect ecosystems,
3. Protect underground sources of drinking water and other natural resources,
4. Ensure market confidence in emission reductions through regulatory clarity and proper GHG accounting, and
5. Facilitate cost-effective, timely deployment.

The Guidelines complement many of the emerging regulatory frameworks for CCS, including the U.S. EPA Underground Injection Control (UIC) Draft Class VI Rule for Geologic Sequestration and the EU Directive for Geologic Sequestration. This paper reviews the similarities and differences between the Guidelines, the U.S. U.S. EPA proposal, and the EU Directive. Because of the broad stakeholder input in developing the Guidelines, and because they address many of the same issues covered by the emergent regulation, such a comparison is useful in informing the global development of CCS regulations and ultimately best practices.

2. Comparative Analysis Methodology

For this review, we consider the WRI CCS Guidelines [1], as opposed to the background text that is included in the Guidelines document. Similarly, we consider the U.S. EPA draft rule text (pages 43534-43541 from the July 25, 2008 Federal Register Notice) [2] -- not the preamble to the rule, and the amendments included in the EU Directive proposal (2008/0015) [3] -- not the text in the existing Directives.

Each process was predicated on a unique and somewhat different scope. The WRI CCS Guidelines address the capture, transport, and storage of carbon dioxide (CO_2) while the U.S. EPA Draft Rule is focused on the protection of drinking water during injection and storage. Both capture and transport are outside the purview of the U.S. EPA's authority under the Safe Drinking Water Act. The EU Directive is the result of a unique process that is not directly comparable to the WRI or U.S. EPA processes but resulted in a similar set of rules. Despite the differences in approach and limitations of the comparison, we believe it is valuable to compare the three documents. We are particularly interested in the areas where the three approaches came to similar conclusions.

3. Similarities

The WRI CCS Guidelines are largely consistent with the draft U.S. EPA UIC Class VI rule and EU Directive. There is convergence in the approaches to CCS in all three documents, which suggests an emerging global consensus surrounding regulation and best practices for CCS demonstration and deployment. In many ways the similarities between the U.S. U.S. EPA approach, EU Directive and WRI CCS Guidelines are more important than the differences because they demonstrate this convergence. A summary of these similarities is presented in Table 1.

Of the many similarities shown in Table 1, perhaps the most significant is establishing criteria for site selection. All three frameworks require the presence of a cap rock that is laterally extensive, relatively thick, and without penetrations or faults that are predicted to serve as conduits for CO_2 outside the injection reservoir in addition to the presence of an injection formation that can store the anticipated volume of CO_2.

Another significant similarity among the frameworks is the need for a monitoring area that reflects the site-specific geological conditions and that is based on modeling that employs site-specific data. This area may change throughout the course of a CCS project and may need to be periodically re-evaluated. Also important is the universal absence of a standard suite of default monitoring technologies. The development of a site-specific monitoring plan that is based on the unique local geologic conditions and informed by site-specific data collected during characterization is critical to the success of storage at any one site.

The three frameworks identify data requirements for operational monitoring that are largely consistent. For example, all recommend that an operator report the composition of the injected fluid, the volume injected, the flow rate, and reservoir pressure. Each also includes a modeling requirement and mentions or implies integration of this modeling with data collected during operational monitoring as well as site characterization (or exploration). This integrated planning is important to the overall success of CCS operations because by updating the model periodically with monitoring data, in the time the model can better resemble geologic conditions in the field and better predict CO_2 behavior in the subsurface.

All three of the frameworks also emphasize the need for identifying potential leakage pathways and evaluating them in the context of modeling that is based on site-specific data. A site specific risk analysis that is informed by data collected during characterization and operations is essential in ensuring successful site selection and operation. Similarly, having plans in place to manage any unexpected movement of CO_2 is critical to responsible CCS operations. Finally, all evaluated frameworks include the area of elevated pressure that is associated with the injected CO_2 as a consideration for modeling, monitoring, and risk assessments.

4. Differences

Table 2 summarizes the main differences between the WRI CCS Guidelines, the U.S. EPA's Draft Class VI Rule, and the EU Directive on Geological Sequestration. While there are important technical differences, they do not present significant challenges to moving forward with major CCS demonstration projects. U.S. EPA and WRI CCS Guidelines take consistent approaches regarding CO_2 composition. U.S. EPA identifies any stream including important constituents as hazardous wastes subject to RCRA, while the Guidelines define CO_2 and include details on what co-constituents may be present based on the capture technology chosen. The EU takes the OSPAR "overwhelmingly CO_2" position. Although these three approaches seem largely consistent, the legal interpretation can have influence on real projects. Geologic reservoirs have faults and fractures and although all three frameworks identify understanding faults and fractures as an important effort, the language surrounding which types of faults to evaluate differs. In the context of the CCS Guideline development, the stakeholder group vetted several potential definitions for which types of faults are important. Although the group agreed with the premise of avoiding faults or fractures that would lead to leaks, there was concern that a broad statement that required mapping of all faults would be impossible to enforce. The language in the Guidelines identifies "potentially significant transmissive faults" with a focus on those that transect the storage reservoir and the confining zone. The Draft U.S. EPA language requires mapping of all faults and states that sites should "be free of transmissive faults (faults or fractures with sufficient permeability and vertical extent to allow fluids to move between formations)." The EU Directive, like the U.S. EPA approach takes a broad definition and requires a description of faults and fractures as part of site characterization.

Estimating capacity as part of site characterization is emphasized in both the WRI CCS Guidelines and the EU Directive, with a specific mention of volumetric capacity estimates. In the U.S. EPA draft rule, capacity estimates are only required implicitly as part of an "area of review" calculation and in the UIC context which requires adequate pore volume for storage. By stating capacity estimates as an explicit requirement, the Guidelines and EU Directive may provide a more direct tie to the capture component of a CCS effort with an implicit need to prove availability of the needed capacity. This difference may be an artifact of difference in scope with the U.S. EPA rule exclusively focusing on the storage aspects of a project.

For operations, a key criterion is the allowable injection pressures. In this case, the WRI CCS Guidelines and U.S. EPA Rule directly disagree. The U.S. EPA draft rule states that operators cannot exceed 90% of the fracture pressure and the WRI CCS Guidelines state that a regulatory framework should not restrict injections above formation parting or fracture pressures. The EU Directive does not include a limit to injection pressures, but does include reporting fracture pressure as a data requirement. The key question and one that may require further research to answer is whether the available storage space will be significantly decreased by and whether certain caprocks would fail at <90% injection pressure.

Of the three frameworks, there are some terms that are not used consistently. Importantly, the term post-closure seems to be used three different ways. The WRI CCS Guidelines have identified this as a period after a demonstration of non-endangerment has been made and after the point at which the operator is no longer responsible for MMV. The U.S. EPA defines post-closure as a period of time after injection but before a site is closed, during which the operator is responsible for MMV. The EU Directive seems to include some post-closure monitoring in this period, indicating that it spans the time period before and after responsibility of the site is transferred. Clearly defined criteria for cessation of monitoring and transfer of responsibility are essential (regardless of what label is given to any one period of time).

The EU Directive provides the most clarity on the transfer of responsibility and outlines the criteria an operator would need to meet to enable transfer to the "competent authority." This is consistent with the language in the WRI CCS Guidelines which calls for the creation of an entity that can conduct any needed activities at a closed site. The WRI CCS Guidelines differ from the EU Directive in that they allow for these activities to include MMV. The U.S. EPA does not clearly define what happens to a site after the default 50 year post-closure monitoring and permanent closure of the site. This is an area where all three frameworks might offer better clarity on what the competent/authority or entity should do to ensure that a closed site remains safe.

Each evaluated framework takes a slightly different approach to the monitoring duration. Both the WRI CCS Guidelines and the EU Directive take a performance-based approach where the operator is required to demonstrate that the storage is secure. However, as stated previously, the WRI CCS Guidelines would allow for some MMV to continue after this determination is made, under the auspices of the entity that is responsible for the site during the post-closure phase. The U.S. EPA rule calls for monitoring to take place until the plume stabilizes and uses a default period of 50 years for MMV activities, which can be lengthened or shortened at the discretion of the regulator.

The EU Directive outlines clearly that permits for site characterization (or exploration) should be issued separately from permits for site storage. Both the WRI CCS Guidelines and the U.S. EPA Rule are silent on this point, although some states do require separate permits for characterization and injection. The merits of a phased permitting structure should be evaluated in a comprehensive manner because of the needed integration among phases of a storage project with data collected during site characterization informing the storage plans.

Finally, there is a notable difference between the WRI CCS Guidelines and U.S. EPA's Draft rule regarding well construction requirements, specifically on the topic of cementing. The U.S. EPA rule requires long string casing to be cemented to the surface, while the WRI CCS Guidelines specific extending the casing to at least an area above the confining zone. A number of WRI stakeholder felt cementing to the surface should not be required at present because the literature is unclear. Future work should clarify the optimal well construction for permanent geologic storage. The EU Directive does not prescribe construction techniques and cannot offer a basis for comparison.

Table 1. Important similarities between the three frameworks

KEY ISSUE	WRI CCS GUIDELINES	U.S. EPA	EU DIRECTIVE
Siting requirements that focus on geologic characteristics	Specific guidelines given for site characterization and selection, including a set of guidelines for (1) determining the functionality of confining zones(s), (2) determining injectivity and (3) determining capacity (Storage Guidelines, box 5).	The geologic system must be comprised of (1) an injection zone of sufficient areal extent, thickness, porosity and permeability to receive total anticipated volume of CO_2 (2) a confining zone(s) that is free of transmissive faults or fractures and sufficient areal extent and integrity to contain injected CO_2 stream and displaced formation fluids and allow injection at proposed maximum pressures and volumes without initiating or propagating fractures in the confining zone(s) (§146.83)	The site characterization permit (issued prior to the storage permit) includes a four-step process for site selection. The data collection requirement (step 1) includes collection of site-specific data, including reservoir engineering (including volumetric calculations of pore volume for CO_2 injection and ultimate storage capacity, pressure and temperature conditions, pressure volume behavior as a function of formation injectivity, cumulative injection rate and time) (Annex 1, Step 1)
Flexible monitoring area	Monitoring area should be based initially on knowledge of the regional and site geology, overall site-specific risk assessment and subsurface flow simulations. This area should be modified as data obtained during operations warrants. (Storage Guideline 1d)	Area of review is based on computational modeling that accounts for physical and chemical properties of all phases of CO_2 stream. Periodic reevaluation of delineation is required (§146.84)	One component of establishing a monitoring plan is inclusion of…. (c) monitoring locations and spatial sampling rationale (d) frequency of application and temporale sampling rationale (Annex II)
Flexibility in choice of monitoring tools	Operators should have flexibility to choose specific monitoring techniques and protocols that will be deployed at each storage site, as long as methods selected provide data at resolutions that will meet stated monitoring requirements. (Storage Guideline box 1b)	"The testing and monitoring plan must be submitted with the permit application, for Director approval, and must include a description of how the owner or operator will meet the requirements of this section." (§ 146.88) Note: U.S. EPA rule does require minimum monitoring and gives some specificity with respect to corrosion monitoring in the well.	Choice of monitoring technology shall be based on best practice available at the time of design. The directive provides three technology selection options that shall be considered and used as appropriate. (Annex II)
Monitoring and data collection	MMV requirements should not prescribe methods or tools, rather they should focus on key information an operator is required to collect for each injection well and overall project, including: injected volume; flow rate or injection pressure; composition of injectate; spatial distribution of CO_2 plume; reservoir pressure; well integrity; determination of any measurable leakage; and appropriate data (including formation fluid chemistry) from monitoring zone, confining zone and underground sources of drinking water (USDWs). (Storage Guidelines box 1a)	Reporting requirements outlined in § 146.91 include reporting the characteristics of CO_2 stream; injection pressure, flow rate, volume and annular pressure (monthly averages), volume of CO_2 injected, as well as other criteria.	Parameters to be monitored are identified so as to fulfill the purposes of monitoring. However, plan shall in any case include continuous or intermittent monitoring of following items: Fugitive emissions of CO_2 at injection facility; CO_2 volumetric flow at injection wellheads; CO_2 pressure and temperature at injection wellheads (to determine mass flow); Chemical analysis of injected material; Reservoir temperature and pressure (to determine CO_2 phase behavior and state). (Annex III)
Model update requirements	The reservoir and risk models should be recalibrated (or history matched) periodically based on operational data and re-run flow simulations; immediate updates should be made if significant differences in expected and discovered geology are found. (Storage Guideline Box 6f) Operational data should be collected and analyzed throughout a project's operation and integrated into reservoir model and simulations. Data collected should be used to history-match (calibrate) the project performance to the simulation predictions. (Storage	Predict, using computational modeling, the projected lateral and vertical migration of CO_2 plume and formation fluids in subsurface from commencement of injection activities until plume movement ceases, pressure differentials sufficient to cause movement of injected fluids or formation fluids into a USDW are no longer present, or after a fixed time period as determined by the Director. The model must be based on detailed geologic data collected to characterize the injection zone, confining zone and any additional zones; and anticipated	The data collected from monitoring shall be collated. The observed results shall be compared with behaviour predicted in dynamic simulation of 3-D-pressure-volume and saturation behaviour undertaken in the context of the security characterization... Where there is a significant deviation between observed and predicted behaviour, the 3-D-model shall be recalibrated to reflect the observed behaviour. Recalibration shall be based on the data observations from monitoring plan, and where necessary to provide confidence in the recalibration assumptions, additional data shall be obtained. (Annex II, section 1.2)

	Guideline Box 6m)	operating data, and Take into account any geologic heterogeneities, data quality, and their possible impact on model predictions; and (§ 146.84)	
Risk analysis and contingency plans	A risk assessment should be required along with development and implementation of a risk management and risk communication plan for all storage projects. Risk assessments should, at a minimum, examine potential for leakage of injected or displaced fluids via wells, faults, fractures and seismic events, and fluid's potential impacts to integrity of confining zone and endangerment to human health and environment. (Storage Guideline 2a)	§ 146.84 outline the criteria for the area of review and corrective action. In this section it states that the model must "consider potential migration through faults, fractures, and artificial penetrations." An emergency and remedial response plan is also required as outlined in § 146.94	Security, sensitivity and hazard characterization are outlined as requirements. Specifically, the risk assessment should include an exposure assessment, an effects assessment, and a risk characterization. (Annex 1, Step 4)
Inclusion of area of elevated pressure	Storage project footprint is defined as the area above the "injected or displaced fluids". This area is the focus of many Guidelines, including those for Monitoring, Risk Analysis, and Post-Closure non-endangerment criteria (Storage Guidelines 1d, 2a, and 7d)	Pressure front is defined as "the zone of elevated pressure that is created by the injection of carbon dioxide into the subsurface. For GS projects, the pressure front of a CO_2 plume refers to the zone where there is a pressure differential sufficient to cause the movement of injected fluids or formation fluids into a USDW." This pressure front is included as part of geologic storage project definition. Location of this area is included as a monitoring requirement (§ 146.90 and § 146.93)	Pressure volume behaviour is included as a requirement for site characterization in the context of modeling and monitoring. (Annex I)

Table 2. Important differences between the three frameworks

KEY ISSUE	WRI CCS GUIDELINES	U.S. EPA	EU DIRECTIVE
CO_2 composition	Guidelines text outlines quantity of potential co-constituents on a % volume bases. A future action is to compare these with criteria listed under 40 CFR part 261.	Rule does not apply to streams that meet the definition of a hazardous waste under 40 CFR part 261 Hg) (see Definitions)	Necessitates imposing constraints on composition of CO_2 stream, consistent with the primary purpose of geologic sequestration, which is to isolate CO_2 emissions from atmosphere, and that are based on the risks that contamination may pose to safety and security of transport and storage network. Composition of CO_2 stream should be verified prior to injecting and storing it. (Text with EEA Relevance, line 20)
Faults	Operators should identify and map all potentially significant transmissive faults, especially those that transect the confining zone within the project footprint (Storage Guidelines, box 5b5)	Confining zone that is free of transmissive faults or fractures (defined as: faults or fractures with sufficient permeability and vertical extent to allow fluids to move between formations). (§ 146.83)	Characterization includes development of a 3-dimensional static geological earth model that characterizes storage complex in terms of the Presence of any faults or fractures and fault/fracture sealing (Annex 1, Step 2, c)
Volumetric capacity	Operators should estimate or obtain estimates of pore volume with site-specific data for the project footprint. This should include all target formations of interest, including primary and secondary targets. Capacity calculations should include estimates of net vertical volume effectively utilized or available for storage and an estimate of likely pore volume fraction to be used. (Storage Guidelines, box 5d1)	Implicit in description of Area of Review determination, but not required explicitly.	Data collection includes "Reservoir engineering (including volumetric calculations of pore volume for CO_2 injection and ultimate storage capacity, pressure and temperature conditions, pressure volume behaviour as a function of formation injectivity, cumulative injection rate and time)" (Annex 1, Step 1)
Injection pressures	Injection pressures and rates should be determined by well tests. Injection formation parting pressure should not be restricted by a regulatory framework but may be adopted as a best practice for early projects. (Storage Guidelines, box 6j)	"Except during stimulation, the owner or operator must ensure that injection pressure does not exceed 90 percent of the fracture pressure of the injection zone." (§ 146.88) Preamble states that U.S. EPA is seeking comments on this	Fracture pressure is mentioned as a data collection requirement; no restriction set. (Annex 1, Step 1)
Post-closure	Defined as period of time after certification of site closure. At this stage, the storage project should not endanger human health and environment. Guidelines propose a set of expectations for a site in the post-closure period as well as potential mechanisms for managing post-closure MMV activities, to the extent needed. (Definitions)	Post-injection site care means appropriate monitoring and other actions (including corrective action) needed following cessation of injection to assure that USDWs are not endangered as required under § 146.93 (Definitions)	'post-closure' means the period after the closure of a storage site, including the period after the transfer of responsibility to the competent authority (Chapter 1, line 19)
Transfer of responsibility	Certified closed sites should be managed by an entity or entities whose tasks would include activities such as operating registries of sites; conducting periodic MMV; and, if need arises, conducting routine maintenance at MMV wells at closed sites over time. (Storage Guideline 8a)	Site is only closed after a default 50 year post closure monitoring and site closure plan is complete. No transfer is mentioned, but operator has completed obligations at site closure (which is after the post-injection monitoring period) (§ 146.93)	After storage site has been closed, operator should remain responsible for maintenance, monitoring and control, reporting, and corrective measures pursuant to requirement of the Directive on the basis of a post-closure plan… until the responsibility for storage site is transferred to the competent authority. (Chapter 1, line 25)
Monitoring duration	Site is closed when criteria for non-endangerment have been demonstrated and at that time operator is no longer responsible for MMV; However, language leaves open the possibility for longer-term MMV "….In the event that regulators or a separate entity decide to undertake post-closure monitoring that involves keeping an existing monitoring well open or drilling new monitoring wells, project operators should not be responsible for any such work or associated mitigation or remediation arising out of conduct of post-closure	"The owner or operator shall continue to conduct monitoring as specified in the Director-approved post-injection site care and site closure plan for at least 50 years following the cessation of injection. At the Director's discretion, the monitoring will continue until the geologic sequestration project no longer poses an endangerment to USDWs." An exemption may be granted by the director. (§ 146.93)	"Post-closure monitoring shall be based on the information collected and modeled during the implementation of the monitoring plan" It shall serve in particular to provide information required for transfer of responsibility. This is to document that the stored CO_2 will be completely contained for the indefinite future. (Annex II; Article 18)

	MMV. (Storage Guideline 7d, 7e)		
Phased permitting	No recommendation for or against phased permitting.	Draft rule requires submittal and periodic re-evaluation of several types of plans but does not specify a phased permit structure.	Exploration and storage permits are distinct with unique requirements for each. (Chapter 2, Chapter 3)
Cement requirements	The cement in the well should extend from the injection zone to at least an area above the confining zone. (Storage Guidelines, box 6g)	Surface casing must extend through base of lowermost USDW to the surface; one long string casing must extend to injection zone and cemented to surface in one or more stages. (§ 146.86)	No language specific to well construction or cement requirements.

5. Conclusions and Areas needing further clarification

A certain level of humility is needed with any estimate of geologic storage potential. Ultimately the issues of faults, capacity, and injection pressures are interrelated. The WRI CCS Guidelines approach is driven by site-specific data collection and development of project plans that reflect the geology of a specific site. Stakeholders feel strongly that this approach will ultimately lead to the regulators reviewing the site-specific plans rather than requiring a metric that may or may not fit the local geology. Incorporating heterogeneity among (and sometimes within) geologic reservoirs into the confines of a regulatory framework can be a challenge. There will be some degree of uncertainty in geologic storage projects that is expected and managed. A regulatory framework should allow flexibility to adapt as data collected informs the operators understanding of the subsurface.

The requirements for post-closure and responsibility for sites over the long term is an area that all three frameworks in some ways fall short. They acknowledge the potential value of long-term management without attempting to identify what parameters need to be managed, why they need to be managed and for how long they should be managed. These questions may only be answered with experience from integrated CCS Demonstrations.

In a world with widespread CCS deployment, we can envision concerns about several projects utilizing one large geologic storage formation. When several projects are using the same storage reservoir, the operators will need an integrated understanding of the potential impacts one project may have on another. Ultimately, a regulatory framework should protect the projects' footprints from interacting. In this context there is also a need for better clarity regarding reporting and registering sites, especially if the project footprints cross state or national boundaries.

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